# RELAP5/MOD3.2 ANALYSIS OF NATURAL CIRCULATION TEST AT KOZLODUY NPP UNIT 6

**M. Pavlova, P. Groudev**
***Institute for Nuclear Research and Nuclear Energy – Bulgarian Academy of Sciences***
*Tzarigradsko Shaussee 72, Sofia 1784, Bulgaria*

**V. Hadjiev**
***Kozloduy Nuclear Power Plant***

**J. Roglans**
***Argonne National Laboratory***
***9700 So. Cass Avenue, Argonne, Illinois, 60439, USA***

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## ABSTRACT

This paper discusses the results of the thermal-hydraulic investigations of the "Natural Circulation" test at Unit 6, Kozloduy NPP. The RELAP5/MOD3.2 computer code has been used to simulate the Natural Circulation in a VVER-1000 Nuclear Power Plant (NPP) model. A model of the Kozloduy Unit 6 has been developed for the systems thermal-hydraulics code RELAP5/MOD3.2 [1]. This model was developed at the Institute for Nuclear Research and Nuclear Energy – Bulgarian Academy of Sciences (INRNE-BAS), Sofia. This paper presents a summary of the effort involved in defining a RELAP5 validation benchmark problem based on operational data from Kozloduy NPP and performing the analysis. The purpose of the experiment, which was done according to the "Program for investigation of primary side natural circulation of coolant on NPP", was to explicitly establish the response of the plant under primary loop natural circulation conditions. The possibility to remove approximately 150 MW using the natural circulation was also demonstrated during the test. The comparisons between the RELAP5 results and the test data indicate good general agreement. This report was possible through the participation of leading specialists from Kozloduy NPP and with the assistance of Argonne National Laboratory, under the International Nuclear Safety Program (INSP) of the United States Department of Energy.

## 1. INTRODUCTION

Since experimental facilities are usually scaled down models of real plants, there is an additional need to evaluate accident analysis code performance in actual plant conditions. Usually the plant conditions are not well known, plant transients provide very little data and for safety reasons, the parameters are kept away from limiting conditions where most of the code uncertainties lie. A task was initiated to define a benchmark problem for validation of thermal-hydraulics codes for application to Soviet-designed VVER-1000 reactors based on actual plant data. This task will be enveloped in the INSP project for the validation of RELAP5/MOD3.2 for application to VVER-type reactors. Most of the standard problems used in this validation program are based on test data from experimental facilities rather than plant transient measurements. Therefore, the definition of plant-based standard problems is a valuable addition to the validation database.

A plant experiment on natural circulation based on operational data from Kozloduy NPP Unit 6 was selected as a benchmark for the project. The selection was based on the criteria established in the RELAP5 Code Validation Guideline [2], primarily importance to safety and availability and suitability (quality) of the plant data collected during the test. The benchmark has been analyzed with RELAP5/MOD3.2. The calculation results have been used to assess the code for its adequacy to model the benchmark problem for application to VVER-1000 reactors.

The scenario for the Investigation of Natural Circulation on Unit 6, Kozloduy NPP, was part of the project: “Safety Analysis Capability Improvement of KNPP in the field of Thermal-Hydraulic Analysis – KNPP-1000/V320 Transient Plant Data for RELAP5/MOD3.2 Model Validation”. The reference power plant for this analysis is Unit 6 at The Kozloduy NPP site. Operational data from Kozloduy NPP are available for the purpose of assessing how the RELAP5 model compares against plant data.

A model of the Kozloduy Unit 6 was developed for the systems thermal-hydraulics code RELAP5/MOD3.2 [1]. The initial validation of VVER-1000 RELAP5 model was completed and was described in model verification reports [3, 4]. This model was developed at the Institute for Nuclear Research and Nuclear Energy and is applicable to analysis of operational occurrences, abnormal events, and design basis scenarios. The model provides a significant analytical capability for the specialists working in the field of the NPP safety.

The following sections of this report include a description of VVER-1000 power plant, description of the test being studied, a description of the RELAP5/MOD3.2 input model, results, and conclusions.

## 2. VVER-1000 NUCLEAR POWER PLANT DESCRIPTION

The reference power plant for this analysis is Unit 6 at The Kozloduy NPP site. This plant is a VVER-1000 Model V320 [5, 6, 7] pressurized water reactor that produces 3000 MW thermal power and generates 1000 MW electric power. The basic design of a VVER-1000 plant comprises: a pressurized water reactor of 3000 MW thermal power with 163 hexagonal fuel assemblies in the core, and 10 absorbing rod banks, located in 61 fuel assemblies; four primary loops; and one turbogenerator (1500 rpm) producing 1000 MW of electric power. The reactor vessel has 4 inlet nozzles of ∅ 850 mm and 4 outlet nozzles of ∅ 850 mm to connect to the four primary loops. There are also 4 inlets of ∅ 280 mm for safety injection of boron solution to the upper and lower plena in case of primary loss of coolant. Each loop includes one main circulation pump and a horizontal U-tube steam generator (SG). The behavior of the horizontal SG is very different compared to Western-style vertical SG [5, 6, 7]. For example, the secondary side of the horizontal SG contains much more water and all loss-of-feedwater transients are slower. Steam generators play a very important role in the safe and reliable operation of VVER power plants. They determine the thermal-hydraulic response of the primary coolant system during operational and accident transients.

Under normal operating conditions the primary coolant system functions consists of forced circulation using the full or a partial set of main coolant pumps. Under loss-of-flow (blackout) transient conditions, the core cooling is accomplished by natural circulation of the primary coolant. During transients, a boron solution is injected by the safety system into the primary coolant for reactivity control.

The feedwater (FW) system feeds condensate water into the SG trough the HP Heaters (or their bypass) and controls the SG during normal plant evolutions. The feedwater system includes two turbine-driven FW pumps (FWP), two auxiliary electrically driven FW pumps (AFWP), and ten control valves. In normal mode of operation, the FWPs are used. The AFWPs are turned on when the SG level drops below a setpoint. When the load is less than 50% only one FWP is left in operation. In startup/shutdown modes, when the load is less than 5%, the AFWPs are used for SG FW supply, and the FWPs are tripped off.

## 3. DESCRIPTION OF THE NATURAL CIRCULATION TEST

The Investigation of Natural Circulation on Unit 6, Kozloduy NPP, is an experiment that was conducted by Bulgarian and Russian engineers as a test during the plant commissioning phase at the Kozloduy Nuclear Power Plant - Unit #6. It was part of the start-up tests. The test was done according to the "Program for investigation of primary side natural circulation of coolant on NPP". The purpose of the experiment was to explicitly establish the response of the plant under primary coolant natural circulation conditions. During the transient the possibility to remove approximately 150 MW using natural circulation was also demonstrated. The characteristics of the primary coolant system at 5% reactor power were also checked during the test. The reactor power was increased from 0% power to 5% before initiating the test. When the reactor power reached 5% [150 MW] the four main coolant pumps were tripped. During the test, the plant staff did not interfere with the operation control systems except for withdrawing control group #8 to maintain the reactor power at 5% and to maintain the nominal parameters in the primary side by regulating the Make up/Let down flow rates. Activation of the primary and secondary side control systems did not reach the Reactor Scram Setpoints. All plant systems were available during the transient. Plant parameters were then measured to verify the establishment of natural circulation conditions after the pumps were tripped and demonstrate core coolability.

The test considered in this report can be categorized as a class of transients resulting from power plant equipment failure and perturbing the coolant flow rate through the reactor core. In general, the reason for the failure of the main coolant pumps (MCPs) could be electrical – loss of electrical power. The experiment and the RELAP5 analysis have assumed that the MCP failure is due to the loss of electrical power.

The initial steady state conditions of important plant parameters at 5% power, immediately before starting the Investigation of the Natural Circulation test, are shown in Table 1.

**Table 1.** Initial conditions of the main plant parameters at 5% reactor power, before initiation of the natural circulation test

| N | Parameters | Plant data |
|---|---|---|
| 1 | Reactor power | 151 MW |
| 2 | Primary side pressure - Core Exit | 15.70 MPa |
| 3 | Pressure in MSH | 6.13 MPa |
| 4 | Pump Heads | 0.62 MPa |
| 5 | Pressurizer water level | 520 cm |
| 6 | Cold legs temperature | 554 K |
| 7 | Hot legs temperature | 556.5 K |
| 8 | Pressurizer steam temperature | 617.2 K |
| 9 | SG water levels | 245 cm |
| 10 | Temperature of main feed water | 434.8 K |
| 11 | Make up/Letdown flow rates | 30/30 $m^3/h$ |
| 12 | Emergency feed water flow rates | 160/131 $m^3/h$ |
| 13 | SG pressure | 6.13 MPa |
| 14 | Core Exit temperature /Exit of the Assembly # 09-32 / | 555.3 K |

The basic scenario of the natural circulation transient test is as follows:

1) Under stable conditions, at reactor power of 5%, all MCPs are switched off.

2) One minute after the beginning of the transient the Auxiliary Feed Water Pumps (in Bulgarian VPEN) start to decrease flow rate.

3) Decrease of reactor power from 5% to approximately 4 % due to feed back coefficients. To maintain reactor power at 5%, the operator is withdrawing the control rod group #8 from position 28% to 33%.

4) Make up/Let down system changes its parameters of flow rates (See Table 2)

A more detailed scenario of the main events during the performance of the test is shown in Table 2.

Table 2. List of events during the “Natural circulation" test at Kozloduy NPP Unit 6

| **Time, s** | EVENTS |
|---|---|
| Hour:min:sec<br>00:00:00<br>(04:07:00 – real time ) | All MCPs are switched off |
| 00:01:00 hr | Auxiliary feed water pumps /AFWPs/ start to decrease flow rates |
| 00:01:30 hr | Control group #8 starts withdrawing |
| 00:02:45 hr | Auxiliary feed water (AFW) flow rates starts decreasing |
| 00:03:00 hr | The control group #8 are on level 120 cm |
| 00:03:30 hr | Decreasing of the AFW flow rates up to 25/135 $m^3$/hr<br>FWAP flow rate start increasing |
| 00:03:40 hr | The AFW flow rates are increased up to 75/150 $m^3$/hr<br>AFW flow rates start decreasing |
| 00:04:00 hr | The make up flow rate in primary side starts increasing |
| 00:04:45 hr | Primary side make up flow rate reaches – 18 $m^3$/hr |
| 00:04:50 hr | The letdown flow rate in primary side reaches – 80 $m^3$/hr |
| 00:05:00 hr | The AFW flow rates decreased to 25/130 $m^3$/hr |
| 00:05:50 hr | The make up flow rate in primary side starts decreasing |
| 00:06:15 hr | The make up flow rate in primary side reaches 0 $m^3$/hr<br>the make up/ letdown flow rates in primary side starts increasing<br>the AFW flow rates starts increasing |
| 00:06:25 hr | The make up flow rate in primary side is 32 $m^3$/h ,<br>the letdown flow rate in primary side is 18 $m^3$/h<br>the letdown flow rate in primary side starts decreasing |
| 00:06:30 hr | The letdown flow rate in primary side is 0 $m^3$/hr |
| 00:07:00 hr | The make up flow rate in primary side starts decreasing |
| 00:07:20 hr | The make up flow rate in primary side reaches –18 $m^3$/hr |
| 00:08:10 hr | The make up flow rate in primary side is increased up to 20 $m^3$/h |
| 00:08:30 hr | The AFW flow rates are increased up to 75/150 $m^3$/h |
| 00:08:35 hr | The make up flow rate in primary side is increased up to 20 $m^3$/h |
| 00:09:30 hr | The make up flow rate in primary side is increased up to 30 $m^3$/h |

| | |
|---|---|
| 00:09:50 hr | The letdown flow rate in primary side is increased up to 20 $m^3/h$ |
| 00:10:30 hr | **End** |

## 4. RELAP5/MOD3.2 MODEL

The Baseline input deck for VVER-1000/V320 Kozloduy Nuclear Power Plant Unit 6 was developed by the INRNE-BAS. The initial validation of the Kozloduy VVER-1000 RELAP5 model was completed and was described in verification reports [4]. The model was developed for analysis of operational occurrences, abnormal events, and design basis scenarios. The model provides a significant analytical capability for the specialists working in the field of the NPP safety. Data and information for the modeling of these systems and components were obtained from the Kozloduy documentation and from the power plant staff.

The model was defined to include all major systems of the Kozloduy NPP Unit 6, namely reactor core, reactor vessel, main coolant pumps (MCP), steam generator (SG), steam generator steam line and main steam header (MSH), emergency protection system, pressure control system of the primary circuit, makeup system, safety injection system, steam dumping devices (BRU-K, BRU-A, SG and pressurizer safety valves), and main feedwater system.

In the RELAP5 model of the VVER-1000, the primary system has been modeled using four coolant loops representing the four reactor loops. The RELAP5 model configuration provides a detailed representation of the primary, secondary, and safety systems. The reactor core region is represented by a hot and average heated flow paths and a core bypass channel. The reactor vessel model includes a downcomer, lower plenum, and outlet plenum. The pressurizer (PRZ) system includes heaters, spray, and pressurizer relief capability. The safety system representation includes the accumulators, high and low pressure injection systems, and the reactor scram system. The model of the make up and blowdown systems includes the associated control systems.

The scenario that was followed at the NPP - Kozloduy Unit #6 durind the test was rsimulated in the RELAP5 calculations (See Table 2). Before running the transient calculations the RELAP5 VVER-1000/V320 input model was stabilized at 5 % power. All model parameters have been stabilized very close to the levels recorded at the plant, as shown in Table 1. After establishing steady state conditions with the RELAP5 input model at 5% reactor power, the transient calculation was started.

The following parameters (available from plant data collected during the test) were compared between plant measurements and RELAP5 code calculations:

- Primary side pressure;
- Hot and cold leg temperature;

- Pressurizer water level;
- SG water levels;
- MCP heads;
- SG primary side pressure drop;

## 5. RESULTS AND DISCUSSION

The sequence of events described in section 3 was modeled with the RELAP5 code and the VVER-1000 input model for Kozloduy NPP Unit 6. The model development and validation has focused on the applicability of RELAP5/MOD3.2 to this type of transient. As the overall results show, RELAP5 predicted the plant behavior correctly. The most important parameter behaviors are shown in figures 1 to 6. The calculation was performed up to 10 min (600 sec) of transient time. Before running the investigated transient event the RELAP5 model was run with the real plant equilibrium conditions to establish steady state conditions at 5% power (shown in Section 3, Table 1).

The comparison between the initial conditions of plant data parameters before initiation of the test and the RELAP5 calculations at 5% reactor power (steady state condition at 5% power) are shown in Table 3.

Table 3. Comparison of initial conditions between measured plant parameters and RELAP5 calculations at 5% reactor power

| N | Parameters | Plant data | RELAP5 calculation |
|---|---|---|---|
| 1 | Reactor power | 151 MW | 151 MW |
| 2 | Primary side pressure - Core Exit | 15.70 MPa | 15.5 MPa |
| 3 | Pressure in MSH | 6.13 MPa | 6.136 MPa |
| 4 | Pump Heads | 0.62 MPa | 0.62 MPa |
| 5 | Pressurizer water level | 520 cm | 520 cm |
| 6 | Cold legs temperature | 554 K | 552 K |
| 7 | Hot legs temperature | 556.5 K | 554 K |
| 8 | Pressurizer steam temperature | 617.2 K | 619 K |
| 9 | SG water levels | 245 cm | 245 cm |
| 10 | Temperature of main feed water | 434.8 K | 434.8 K |
| 11 | Make up/Letdown flow rates | 30/30 $m^3/h$ | 30/30 $m^3/h$ |
| 12 | Emergency feed water flow rates | 160/131 $m^3/h$ | 160/131 $m^3/h$ |
| 13 | SG pressure | 6.13 MPa | 6.13 MPa |
| 14 | Core Exit temperature /Exit of the Assembly # 09-32 / | 555.3 K | 553 K |

The transient calculations are compared with the test data in Figures 1 through 6. An important parameter is the pressure in the primary circuit, since this parameter is input to many reactor control systems. Figure 1 presents the measured and the calculated primary pressures during the experiment. As shown, the calculated parameter is almost identical to the measured value. After reaching the setpoint for the cold leg spray at approximately 170.0 sec in the test and the RELAP5 calculation, the safety valve is opened. Due to the lack of pressure difference between the cold leg #1 and the pressurizer there is just a small disturbance of the pressure curve at this moment (at 170.0 sec from the beginning of the transient). The lack of pressure difference between the cold leg #1 and the pressurizer is due to loosing all MCPs at the beginning of the transient. The maximum pressure of 16.5 MPa was reached at 290.0 sec during the experiment and 16.3 MPa was reached in the RELAP5 calculation at the same time. After approximately 400.0 sec the pressure became stable at a new level of 16.0 MPa in both cases (in the RELAP5 calculation and the test).

Comparison of the cold and hot leg coolant temperatures is presented in Figure 2. As it is seen from this figure, the calculation closely follows the results obtained from the experiment. The initial value of the core inlet and outlet temperature in the test data is 2 K higher than the initial value of the hot and the cold leg temperatures predicted in RELAP5 calculations. The reason for this small difference is due to the use of a single value for the secondary side pressure, which defines the primary side parameters, thus neglecting the slight differences among the four loops that occurs in reality. Since the accuracy of the pressure measurement is higher, it was preferred to use the secondary pressure as a reference point.

The pressurizer water levels are compared in Figure 3. The RELAP5 calculated pressurizer water level is the collapsed water level. The trends (level increase and decrease) are the same in the calculation and in the plant data, although there is some difference in the value.

The steam generator water levels are compared in Figure 4. This figure indicates a good agreement between the plant data and the RELAP5 calculation. Note the scale of the plot: the differences are very small.

The main coolant pump head is also an important parameter for the quality of the model predictions. The results from the experiment and RELAP5 are compared on Figure 5.

Figure 6 provides a comparison of SG Primary Side Pressure Difference. As it is shown in this figure, there is also a good agreement between the plant data and the RELAP5 calculation.

## 6. CONCLUSIONS

In general the comparisons indicate good agreement between the RELAP5 results and the experimental data for the natural circulation test conducted in KNPP, Unit 6. Test facilities are frequently scaled down models of the actual power plant; the scaling can increase the uncertainty of the results of the test facility relative to the reactor performance. In this benchmark based on Kozloduy NPP the scaling is not a factor. The results provide an integrated evaluation of the complete RELAP5 VVER-1000 model. The comparisons indicate that RELAP5 predicts the test results very well.

The RELAP5 model developed for the transient analysis of VVER-1000 nuclear power plants has been used to accurately predict the results obtained during the natural circulation test performed at the Kozloduy NPP (Unit 6). These results are an important part of the validation of the RELAP5 model developed for Kozloduy NPP. The overall conclusion is that RELAP5/MOD3.2 is adequate to simulate the transient phenomena occurring in a VVER-1000 under natural circulation conditions. The results presented in this paper will be used for comparative analysis of a RELAP5 validation benchmark problem.

## 7. REFERENCES

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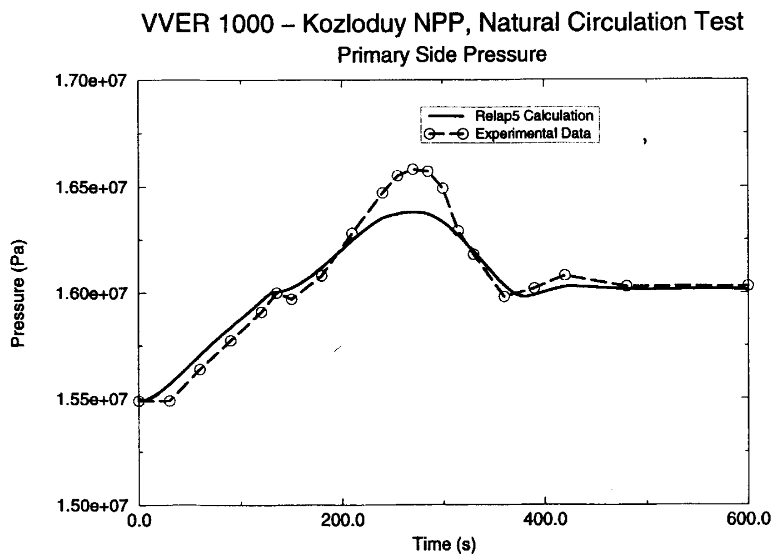


Figure 1.: Comparison of Primary Side Pressure

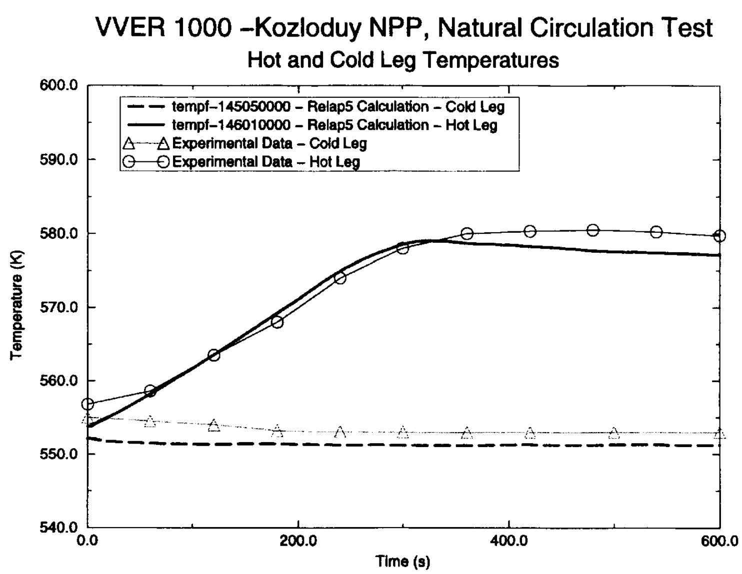


Figure 2.: Comparison of Hot and Cold Leg Temperature

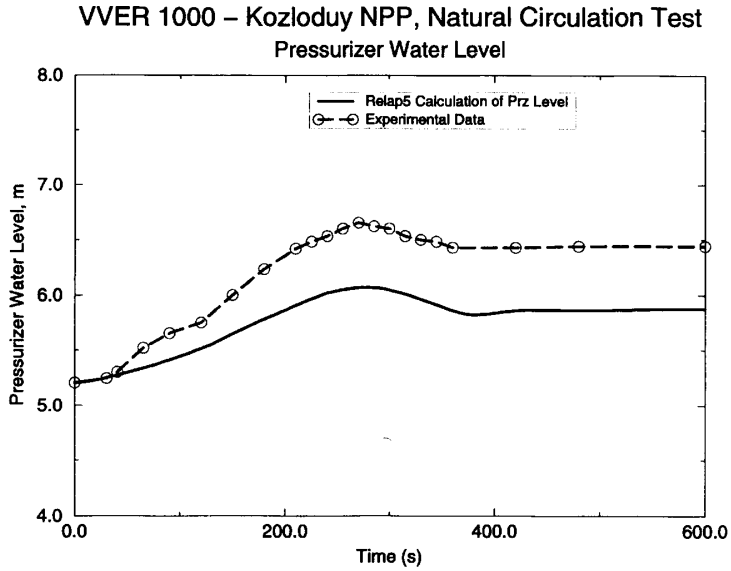


Figure 3.: Comparison of Pressurizer Water Level

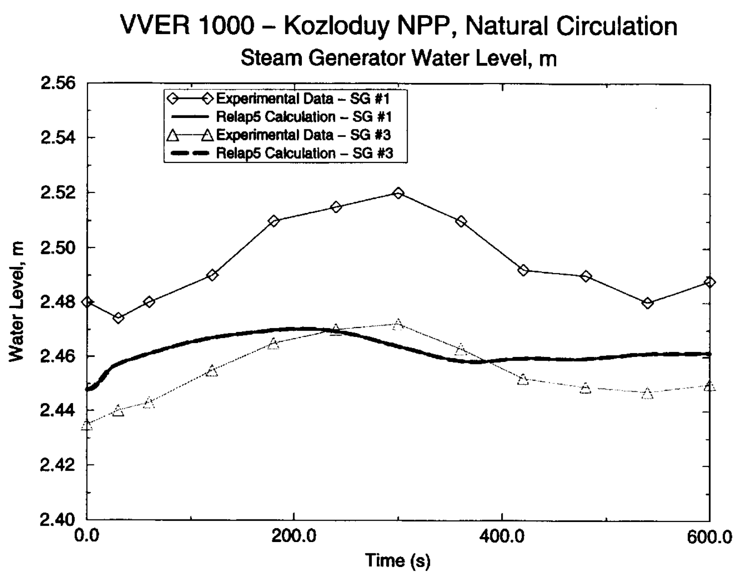


Figure 4.: Comparison of SG Water Levels

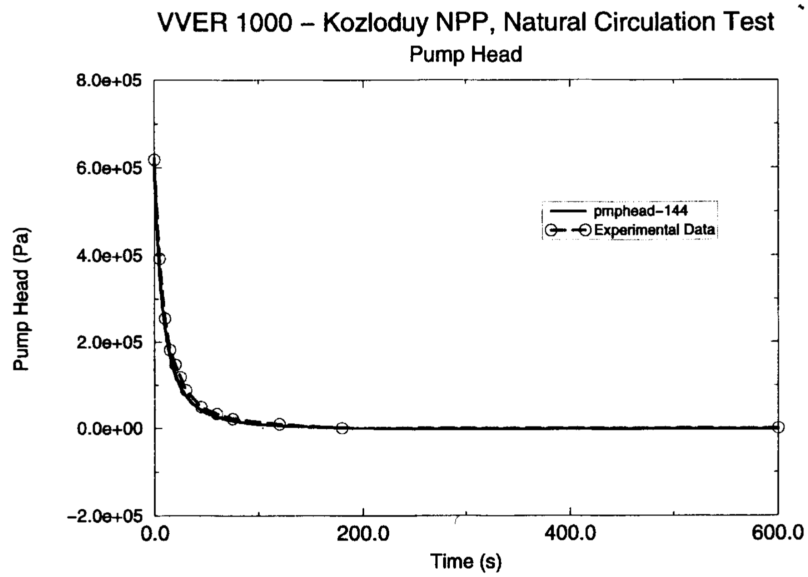


Figure 5.: Comperison of MCP Head

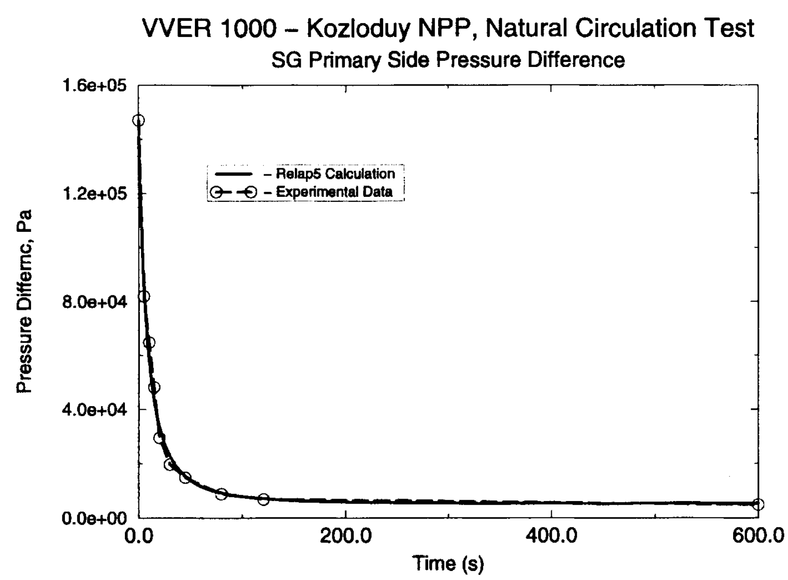


Figure 6.: Comparison of SG Primary Side Pressure Difference